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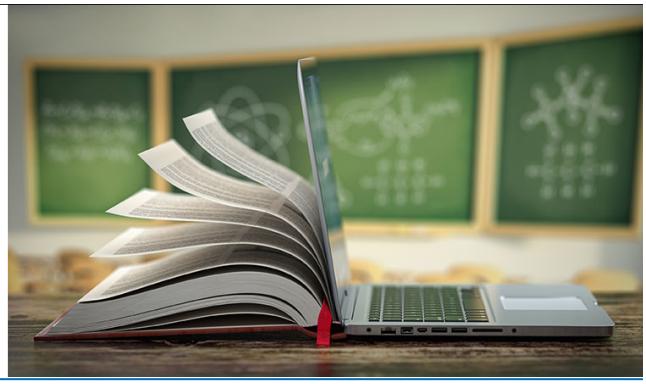

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Study of Physical Properties and Physical Processes in Nano-thin Spatial Dissipative Structures

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Abstract. Two-dimensional geometric object "neutral surface" – successfully used to study thin plates. The use of this two-dimensional geometric object is not possible for the study of physical properties and physical processes in nano-thin SDS (spatial dissipative structures). The SDS lattice undergoes a rotational curvature around three mutually perpendicular directions, and the nano-thin SDS itself remains flat. We have developed a method for the study of nano-thin SDS with rotary lattice curvature. We used as a basis the method of visualizing the rotational curvature of the lattice by constructing a two-dimensional geometric object – the surface of the lattice curvature by nano-thin SDS. This method of investigation involves application of the lattice curvature surface with nano-thin SDS for the selected crystallographic direction as a "neutral surface". The method will find application in nanotechnology.

1. Introduction

For the study of thin plates a two-dimensional geometric object is successfully used – a "neutral surface", that is, the geometric place of the points equally spaced from the upper and lower surfaces of the thin plate [1]. However, the use of the "neutral surface" is not possible for the study of physical properties and physical processes in nano-thin spatial dissipative structures (SDS) [2–8]. The lattice of nano-thin SDS experiences internal bending as opposed to thin plates, and as a whole the lattice of nano-thin SDS remains flat [9].

Really, we will obtain a flat rhomb by constructing a "neutral surface" of nano-thin SDS hexagonal selenium, the lattice of which undergoes elastic rotational curvature around [001]. Thus, the construction the "neutral surface" of the nano-thin SDS with the inner bending of the lattice does not allow visualization of the lattice rotational curvature of the nano-thin SDS.

Visualization can be performed for lattice rotary curvature of nano-thin SDS, namely for nano-thin crystals of hexagonal selenium with elastic rotary curvature of lattice around [001] after stage of hardening of nano-thin SDS [10–13]. We propose a method for visualization of the lattice rotary curvature of nano-thin SDS earlier [10]. The visualization of the rotational curvature of the lattice of nano-thin SDS was achieved by us by constructing a two-dimensional geometric object - the surface of the curvature of the lattice of nano-thin SDS for the selected crystallographic direction (Figure 1).

However, the above method [10] allows visualizing elastic rotational curvature of the lattice of nano-thin SDS, but does not allow investigating physical properties and physical processes in nano-thin SDSs.

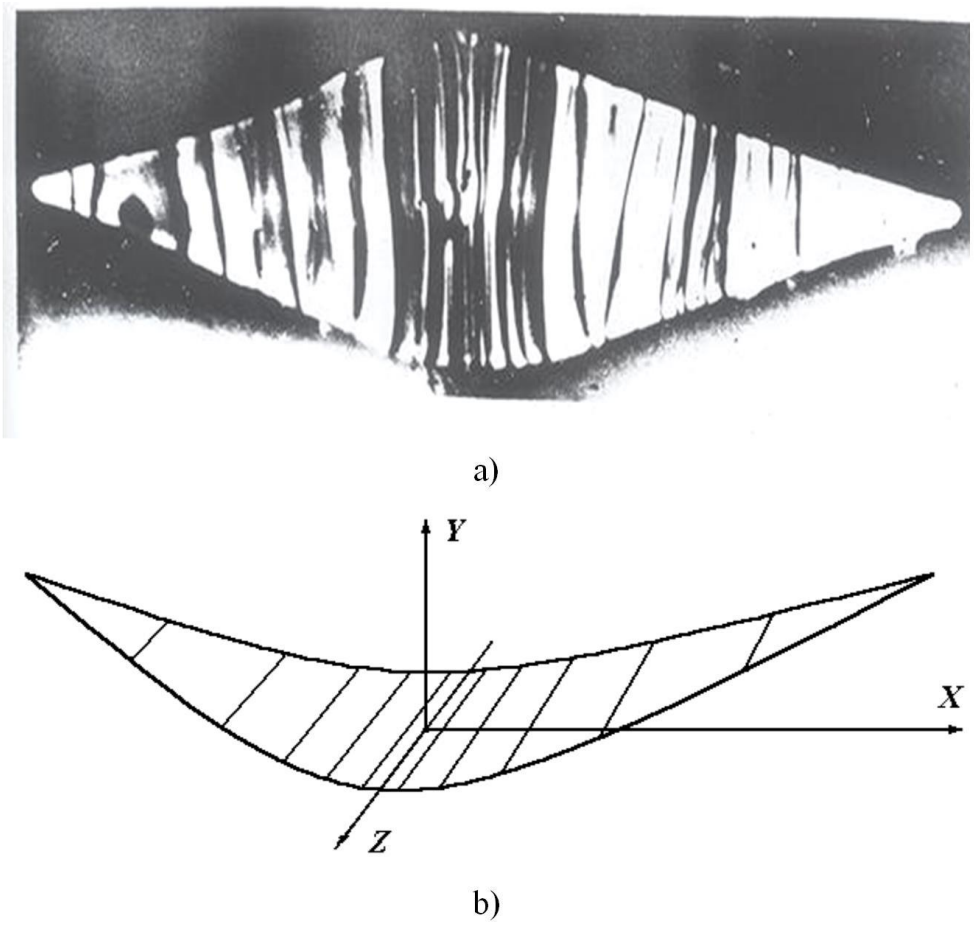

Figure 1. Electron microscopic image of nano-thin diamond-shaped SDS of hexagonal selenium with elastic rotational curvature of lattice around [001] and system of bending extinction contours of parallel [001] coinciding with short diagonal of rhombus, JEM-200CX JEOL Ltd, Japan. a) The lattice curvature surface with a nano-thin SDS for [100] hexagonal selenium, taken as a "neutral surface", the maximum curvature of which coincides with the short diagonal of the rhombus; b) Result of construction the lattice curvature surface with a diamond-shaped nano-thin SDS around [001] for [100].

In view of the above, we have developed a method for investigating nano-thin SDS with rotary lattice curvature. We founded this means of research on the application of the method of visualizing the lattice rotary curvature [10] by constructing a two-dimensional geometric object – the lattice curvature surface with a nano-thin SDS for the selected crystallographic direction. In addition, the above method involves applying the lattice curvature surface of the nano-thin SDS to a selected crystallographic direction as a "neutral surface". Besides, we perform a comparative analysis of the "neutral surfaces" of the nano-thin SDS and the previously studied reference thin plates [1]. This procedure is necessary to identify the bending features of the lattice curvature surface of the nano-thin SDS for the selected crystallographic direction used as the "neutral surface". We are using new information on the bending features of the "neutral surface" of nano-thin SDS to investigate the physical properties and physical processes in nano-thin SDS.

Thus, we propose the following sequence of actions:

1. the two-dimensional geometric object – the lattice curvature surface with nano-thin SDS is created for selected crystallographic direction [10, 11];
2. the lattice curvature surface of the nano-thin SDS for the selected crystallographic direction using as a "neutral surface";
3. a comparative analysis performing of "neutral surfaces" of nano-thin SDS and thin reference plates with previously identified properties and detecting on this basis new information on bending features of the "neutral surface" of nano-thin SDS;
4. new information identified on the features of "neutral surface" bending using to investigate the physical properties and physical processes in nano-thin SDS.

The lattice curvature surface of the nano-thin SDS, used as the "neutral surface" of the nano-thin SDS, allows us to move from solving three-dimensional to solving two-dimensional problems. Indeed, in work [1] it is indicated, "…one can consider the plate as not possessing thickness, that is, as a geometric surface...".

2. Results and discussion

We illustrate the proposed method of investigating physical properties and physical processes in nano-thin SDSs by the following examples.

We investigated the physical property of hexagonal selenium nano-thin SDS using the proposed method. We studied the origin of the interblock torsion boundary at the center of the diamond-shaped nano-thin SDS with elastic rotational lattice curvature. To do this, we constructed the lattice curvature surface with a diamond-shaped nano-thin SDS (figure 1 a) for [100], the lattice of which experiences non-uniform elastic rotational curvature around [001] (figure 1 a) [10–14]. We present the result of the construction the lattice curvature surface with a diamond-shaped nano-thin SDS around [001] for [100] in figure 1 b. We applied the surface lattice curvature of the nano-thin SDS around [001] for [100] (figure 1 b) as the "neutral surface" of the hexagonal selenium nano-thin SDS and established the features of its bending.

We have previously found that the maximum value of the surface lattice curvature of the nano-thin SDS for [100] coincides with the short diagonal of the diamond-shaped nano-thin SDS (figure 1 a) with the inhomogeneous elastic rotational lattice curvature of the nano-thin SDS around [001] [14]. Accordingly, the feature of the "neutral surface" bending of the nano-thin SDS was the maximum curvature of the "neutral surface" of the nano-thin SDS (figure 1 b) in the direction of the short rhombus diagonal.

We performed a comparative analysis of the "neutral surfaces" of the nano-thin diamond-shaped SDS for [100] (figure 1 b), the reference wedge-shaped thin plate and the reference rounded thin disk [1]. As a result, we identified new information on the features of the "neutral surface" bending of nano-thin SDS. Stresses arising from the action of forces on the nano-thin SDS had a maximum value at the center of the long diagonal (Figure 1 b) of the "neutral surface" of the diamond-shaped nano-thin SDS.

The formula of stress distribution in the diamond-shaped nano-thin SDS:

$$\sigma_{rr} = -\frac{2F_1 \cos\phi}{r(\alpha + \frac{1}{2}\sin 2\alpha)} \tag{1}$$

where F_1 is the force acting in the direction of the long diagonal of the diamond-shaped plate; φ is the angle of deviation of the direction of action of the force F_1 from the long diagonal of the diamond shaped plate; α – the angle between the long diagonal of the diamond-shaped plate and the side of the rhombus.

We took into account that the maximum curvature of the lattice curvature surface of the nano-thin SDS for [100] coincides with the short diagonal of the diamond-shaped nano-thin SDS. In addition, we analyzed formula 1 and determined that the maximum value σ_{rr} at the given F_1 force value, α angle

value and r value is achieved at $\varphi = 0$, in other words, along the long diagonal of the diamond-shaped nano-thin SDS. As a result, we concluded that the maximum value σ_{rr} at under the above conditions will be at the intersection point of the diagonals of the diamond-shaped nano-thin SDS, that is, at the center of the diamond-shaped nano-thin SDS.

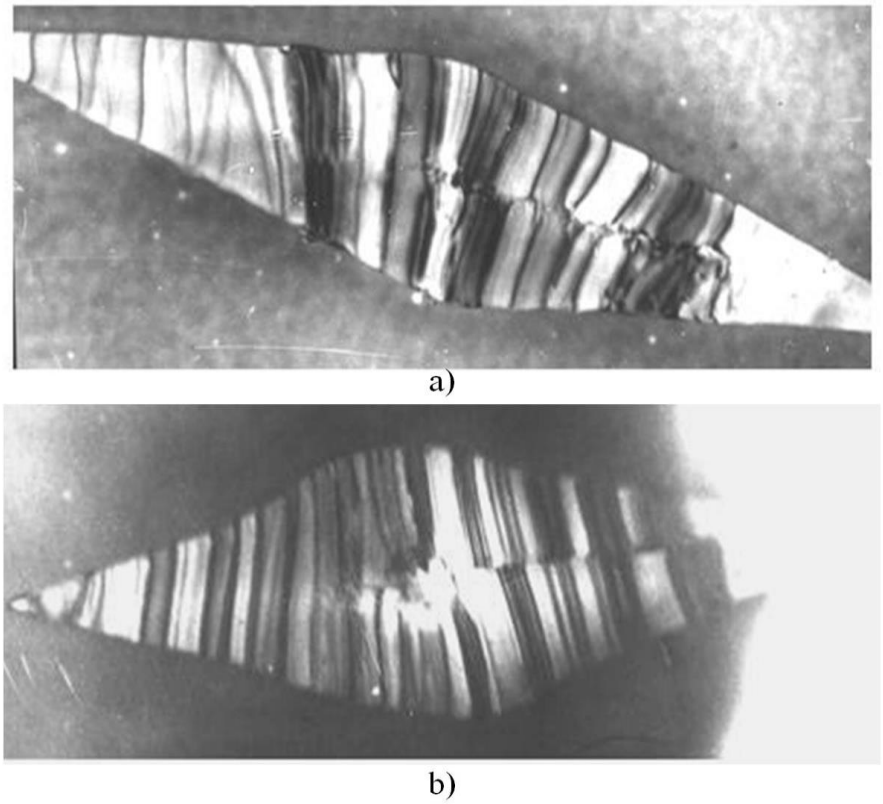

Figure 2. Electron microscopic images of diamond-shaped nano-thin SDS of hexagonal selenium (a, b) whose lattice experiences non-uniform rotational curvature around [001] with interblock torsion boundaries. The above mentioned torsion boundaries originated at the center of the diamond-shaped nano-thin SDS and developed by elongation along the long diagonal of the diamond-shaped nano-thin SDS, up to reaching the growth front of the nano-thin SDS in the amorphous film. JEM-200CX JEOL Ltd, Japan.

New information on the maximum stress value at the intersection point of the neutral surface diagonals of the diamond-shaped nano-thin SDS allowed us to explain the physical property of the nano-thin PDS. Namely, we showed that the emergence of interblock boundaries occurs in the center of diamond-shaped nano-thin SDS [15–17]. We noted that in this experiment, the SDS lattice experiences a non-uniform elastic rotational curvature around [001] (Figure 1 a), (Figure 2 a).

Subsequently, we examined the physical process in nano-thin SDS of hexagonal selenium using the proposed SDS study method. In fact, we studied the process of development of the interblock torsion boundary originating at the point of diagonals intersection of the diamond-shaped nano-thin SDS [18–20], along the long diagonal of the nano-thin diamond-shaped SDS (figure 2 a, figure 2 b). To do this, we constructed a lattice curvature surface with a diamond-shaped nano-thin PDS for [100], the lattice of which experiences non-uniform rotational curvature around [001] [10] (figure 1).

We applied the curvature surface of the nano-thin SDS lattice for [100] (figure 1 b) as the “neutral surface” of the nano-thin SDS and established the features of its bending. We performed a

comparative analysis of the "neutral surfaces" of the nano-thin diamond-shaped PDS hexagonal selenium for [100] (figure 1 b), the reference wedge-shaped thin plate and the reference rounded thin disk [1]. As a result, we identified new information on bending features of the "neutral surface" of the nano-thin SDS. Stresses arising from forces on the nano-thin SDS had maximum values along the long diagonal of the "neutral surface" of the diamond-shaped nano-thin PDS of hexagonal selenium.

This new information allowed us to explain the physical process in the nano-thin diamond-shaped SDS of hexagonal selenium. The above process was the development of the interblock torsion boundary originating in the center of the diamond-shaped nano-thin SDS. Indeed, the development of the interblock torsion boundary originating in the center of the diamond-shaped nano-thin SDS (figure 1 a), (figure 2 a), was realized along the long diagonal of the nano-thin diamond – shaped SDS. Therefore, the process took place along the direction where the stresses arising from the action of forces on the nano-thin SDS had maximum values.

3. Conclusion

Thus, using the proposed method, we investigated and got our explanation the physical property – the origin the interblock torsion boundary at the center of the diamond-shaped nano-thin SDS (Figure 1 a), (Figure 2 a).

Also, with the help of the proposed method, we investigated and got our explanation of the physical process - the development along the long diagonal of the nano-thin diamond-shaped SDS of the interblock torsion boundary [15–20] (Figure 2 a, Figure 2 b).

References

[1] Landau L D and Lifshits E M 1987 *Theoretical physics Theory of elasticity* (Moscow: Science Main edition of physical and mathematical literature) p 60
[2] Prigozhin I and Kondepudi D 2002 *Modern thermodynamics. From heat engines to dissipative structures* (Moscow: World) p 461
[3] Nikolis G and Prigozhin I 1979 *Self-organization in non-equilibrium systems* (Moscow: World) p 512
[4] Nikolis G and Prigozhin I 1990 *Knowledge of complex* (Moscow: World) p 342
[5] Haken G 1985 *Synergetrics. Instability hierarchies in self-organizing systems and devices* (Moscow: World) p 419
[6] Klimontovich Yu L 1990 *Turbulent movement and the structure of chaos: A new approach to the statistical theory of open system* (Moscow: Science) p 320
[7] Ivanovsky A L 1999 *Quantum chemistry in materials science. Nanotubular forms of matter* (Yekaterinburg: UrO RAS) p 175
[8] Bazarov I P, Gevorkyan E V and Nikolaev P N 1989 *Non-equilibrium thermodynamics and physical kinetics* (Moscow: Publishing house MSU) p 240
[9] Bolotov I E and Kolosov V Yu 1980 Bend of thin-film crystals of selenium, found along the extinction contours *Izv. Academy of sciences of the USSR Series physical* **44 6** 1194–1197
[10] Malkov V B, Nikolaenko I V, Shveikin G P, Malkov A V, Pushin V G, Malkov O V and Shulgin B V 2015 *Method for visualization of rotary curvature of the lattice of nanofilament crystals* RU Patent **2570106**
[11] Malkov V B, Nikolaenko I V, Shveikin G P, Pushin V G, Malkov A V, Shulgin B V and Malkov O V 2018 Change in the geometry of the lattice of nano-thin, spatial dissipative structures formed in an amorphous film *Reports of the Academy of Sciences* **166 11** 649–651
[12] Malkov V B, Nikolaenko I V, Shveikin G P, Malkov A V, Pushin V G, Shulgin B V, Malkov O V and Plaksin S V 2017 *Method for obtaining dissipative structures* RU Patent **2637396**
[13] Malkov V B, Nikolaenko I V, Shveikin G P, Pushin V G, Malkov A V, Malkov O V and Shulgin B V 2018 Formation of dissipative structures in amorphous film *Reports of the Academy of Sciences* **478 5** 543–545

[14] Malkov V B, Malkov A V, Malkov O V, Pushin V G, Shulgin B V and Agalakov S P 2008 The phenomenon of elastic rotational curvature of the lattice of nano-thin crystals of hexagonal selenium around [001] as part of the asymmetric theory of elasticity *Collection of report Kharkiv nanotechnol. Assembly* **2** 18–23
[15] Bolotov I E, Kolosov V Yu and Malkov V B 1986 Electron Microscopy Investigation of Crystals Based on Bend-Contour Arrangement 3. Formation of Subgrain Boundaries in Dislocation-Free Crystals of Selenium *Phys. Stat. Sol. (a)* **95** 377–383
[16] Bolotov I E, Kolosov V Yu and Malkov V B 1986 A new type of interblock boundaries in thin-film crystals of selenium *Crystallography* **1** 204–206
[17] Bolotov I E, Kolosov V Yu and Malkov V B 1984 Application of Bend-Contour Method the Investigation of Block Formation in Thin-Film Crystals *Budapest Electron Microscopy* **2** 42–45
[18] Malkov V B, Malkov A V, Pushin V G, Strekalovsky V N and Malkov O V 2012 *Method of diagnosing the effect of changing the sign of the disorientation vector along the interblock boundaries in nanofilament crystals* RU Patent **2534719**
[19] Malkov V B, Nikolaenko I V, Shveikin G P, Pushin V G, Malkov A V, Malkov O V and Shulgin B V 2018 The mechanism of formation of interblock boundaries, the effect of changing the sign of the orientation vector along the broken interblock boundaries in nano-thin spatial dissipative structures *Reports of the Academy of Sciences* **481 1** 30–32
[20] Bolotov I E and Kolosov V Yu 1982 Investigation of Crystals Based on Bend-Contour Arrangement. 1. Relationship between Bend-Contour Arrangement and Bend Geometry *Phys. Stat. Sol (a)* **69 1** 85–96

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